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## HUNTING DOWN INTERPRETATIONS OF THE HERA LARGE- $Q^2$ DATA

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### ABSTRACT

Possible interpretations of the HERA large- $Q^2$  data are reviewed briefly. The possibility of statistical fluctuations cannot be ruled out, and it seems premature to argue that the H1 and ZEUS anomalies are incompatible. The data cannot be explained away by modifications of parton distributions, nor do contact interactions help. A leptoquark interpretation would need a large  $\tau q$  branching ratio. Several  $R$ -violating squark interpretations are still viable despite all the constraints, and offer interesting experimental signatures, but please do not hold your breath.

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# 1 Introduction

The large- $Q^2$ , large- $x$  HERA data reported by the H1 [1] and ZEUS [2] collaborations early in 1997 excited considerable interest, being subject to many theoretical interpretations and stimulating many related experimental searches. The new instalment of HERA data and other experimental data reported here cast new light on many of the suggested interpretations. Now is an opportune moment to take stock of the situation, assess which interpretations remain viable, and review how those remaining might be elucidated by future analyses. Space restrictions do not permit me to do justice to the many papers on this subject, and what follows is a personal selection of material: for other recent reviews, see [3].

## 2 Statistical Fluctuations?

H1 and ZEUS reported here the current status of their 1997 neutral-current data analysis [4], in addition to the data published previously [1, 2]. H1 has by now found  $7+1=8$  events vs.  $0.95+0.58 = 1.53 (\pm 0.29)$  background in the window  $M_e = 200 \pm 12.5$  GeV,  $y_e > 0.4$  [5], and ZEUS has  $4+1=5$  events vs.  $0.91 + 0.61 = 1.51 (\pm 0.13)$  background in the window  $x > 0.55, y_{D_A} > 0.25$  [6], and they quote respectively probabilities of 1% (1.9%) for such a fluctuation in any window (in the quoted window). These probabilities are not negligible, but one should be impressed if one could be convinced that the two experiments were seeing compatible anomalies – more on this shortly. It is important to note that, although the 1997 data do not repeat the magnitudes of the anomalies reported in the earlier data, this year's data are not below the rates expected in the Standard Model.

In addition, the HERA collaborations have reported apparent excesses in their charged-current data: H1 has found 14 events vs.  $Q^2 > 10^4$  GeV<sup>2</sup>, compared with  $8.33 \pm 3.10$  expected [5], and ZEUS has 15 events vs  $9.4 \pm 2.5 \pm 1.6$  expected [6]. These excesses are intriguing, but not as significant as those reported in the neutral-current samples.

For the moment, we conclude that statistical fluctuations cannot be excluded, even if they are formally unlikely.

## 3 Are the H1 and ZEUS Anomalies Compatible?

The reported excesses are apparently in different kinematic regions: H1 discusses the region  $M_e = 200 \pm 12.5$  GeV (corresponding naïvely to  $x_e = 0.45 \pm 0.06$ ) and  $y_e > 0.4$  [5], whereas ZEUS discusses  $x_{D_A} > 0.55$  and  $y_{D_A} > 0.25$  [5]. However, the two collaborations use different measurement methods – H1 using electron measurements and ZEUS the double-angle method – with different statistical and systematic errors. In particular, the methods are affected differently by initial-state photon radiation [7, 8, 9], the possible effects of gluon radiation have not been evaluated completely, and detector effects such as the energy calibrations cannot be

dismissed entirely.

The most complete analysis, using all the available measured quantities, indicates that the experiments' apparent mass difference  $\Delta m = 26 \pm 10$  GeV should be reduced to  $17 \pm 7$  GeV, on the basis of which it seems that the decay of a single narrow resonance is unlikely [10, 5].

In my view, it is premature to exclude a resonance interpretation. I personally would like to see a more complete treatment of gluon radiation using the full perturbative-QCD matrix element now available [11], the Standard Model backgrounds are non-negligible, and one should perform a global fit to all the large- $x$  data of both collaborations. Nevertheless stocks in models with production of a single leptoquark or  $R$ -violating squark decaying into  $eq$  final states are surely going down.

## 4 Modified Parton Distributions?

Forgetting for the moment about possible structures in the  $x$  distributions, could the global excess at large  $x$  and  $Q^2$  be accommodated by modifications of the conventional parton distributions used to predict Standard Model rates? One suggestion was a possible “lump” in the valence quark distribution at  $x \sim 1$  at low  $Q^2$ , but evolution of this “lump” does not have a large effect in the HERA range of  $x$  and  $Q^2$  [12]. An alternative suggestion was intrinsic charm [13], but this is tightly constrained by EMC data on  $\mu N \rightarrow \mu \bar{c} c X$ , and unable to modify significantly the Standard Model predictions if  $c(x) = \bar{c}(x)$  [14]. However, even if one makes  $\bar{c}(x)$  harder than  $c(x)$ , the effect on the HERA neutral-current rate is  $\lesssim 10\%$  in the range  $M = 200 \pm 10$  GeV, though effects up to 50% might be possible in the charged-current rate, and this type of model might provide an alternative interpretation of the CDF high- $E_T$  jet excess [15].

My conclusion is that the proposed modifications of the parton distributions cannot make a significant contribution to explaining the neutral-current data, but they might make a more important contribution to resolving the possible charged-current excess. This is in any case less significant, and I would recommend waiting to see how it develops.

## 5 New Contact Interactions?

Those relevant to the HERA data may be written in the general form

$$\frac{\eta}{m^2} (\bar{e} \gamma_\mu e)_{L,R} (\bar{q} \gamma^\mu q)_{L,R} : \eta = \pm 1, q = u, d \quad (1)$$

giving 16 possibilities, which are tightly constrained by experiments on parity violation in atoms (which, however, allow parity-conserving combinations:  $\eta_{LR}^{eq} = \eta_{RL}^{eq}$  and other, more general, possibilities), by LEP2 measurements of  $e^+ e^- \rightarrow \bar{q} q$ , and by CDF measurements of the Drell-Yan cross section. A recent global analysis [16] of atomic-physics parity-violation experiments,

lower-energy deep-inelastic  $eN$  experiments, LEP, Drell-Yan and the  $Q^2$  distribution of the first instalment of large- $Q^2$  HERA data found fits with  $\chi^2 = 176.4$  for 164 degrees of freedom with no additional contact interactions:  $\chi^2 = 187.1$  for 163 d.o.f. with  $\eta_{LR}^{eu} = \eta_{RL}^{eu}$ , which is *worse*, and  $\chi^2 = 167.2$  for 156 d.o.f. when all possible contact interactions are allowed, which “represents no real improvement over the Standard Model”. The real killer for the contact-interaction fits is the constraint imposed by the CDF Drell-Yan data. Needless to say, no contact interaction would give a resonance peak in the  $eq$  invariant mass! Moreover, the constraints of weak universality make it difficult to arrange a large charged-current signal.

Therefore, I personally conclude that there is no motivation currently to pursue further the possibility of contact interactions.

## 6 Leptoquark?

The tree-level cross section for producing a leptoquark or  $R$ -violating squark in  $ep$  collisions is  $\sigma = (\pi/4s) \lambda^2 F_J$ , where  $F_J = 1(2)$  for scalar(vector) leptoquarks. One-loop QCD corrections to this cross section have been calculated, as well as a number of final-state kinematic distributions [11]. Using the known parton distributions at  $x \sim 0.5$ , it was found that, in order to explain the first batch of HERA data, one needed  $\lambda \simeq 0.04/\sqrt{B(e^+q)}$  if production was via  $e^+d$  collisions, and  $\lambda \gtrsim 0.3/\sqrt{B(e^+q)}$  for production off some  $q$  or  $\bar{q}$  in the sea, where  $B(e^+q)$  is the branching ratio for decay into the observed  $e^+$ -jet final states [7].

The dominant production mechanism at the FNAL Tevatron collider is pair production via QCD, which is independent of  $\lambda$ , and for which the one-loop QCD corrections have also been calculated [17]. Using these, CDF [18] and D0 [19] together imply  $m_{LQ} \gtrsim 240$  GeV for  $B(e^+q) = 1$  for a scalar leptoquark, and a far stronger (though somewhat model-dependent) limit for a vector leptoquark, which option we shall not discuss further. Could the leptoquark have  $B(e^+q) < 1$ ? A large  $B(\bar{\nu}q)$  is difficult to reconcile with charged-current universality [20, 21]. Also, if  $B(e^+q) > B(\bar{\nu}q)$  as suggested by the possible relative magnitudes of the neutral- and charged-current anomalies (19 events with 8 background vs 7 events with 3 background for  $M > 175$  GeV,  $Q^2 > 15,000$  GeV<sup>2</sup>) [5, 6], the FNAL data together imply  $m_{2Q} > 220$  GeV, beyond the range suggested by the HERA data [22]. Moreover, a significant  $B(\mu q)$  is excluded by upper limits on anomalous muon capture on nuclei:  $\mu N \rightarrow eN$  [7]. The only remaining unexcluded decay mode into Standard Model particles is  $\tau q$ , and it would be worthwhile looking for this decay mode at FNAL and/or HERA, so as to pin down or exclude finally the leptoquark interpretation. Failing  $\tau q$ , one needs some decay mode involving particles beyond the Standard Model, and these are provided by the final interpretation we discuss.

## 7 Squarks with $R$ Violation?

The supermultiplet content and symmetries of the minimal supersymmetric extension of the Standard Model (MSSM) admit extra couplings beyond those responsible for the quark and lepton masses:  $\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$ . Any one of these couplings would violate  $R = (-1)^{3B+L+2S}$ . They would provide dilepton, leptoquark and dijet signatures, respectively, and a combination of the  $\lambda'$  and  $\lambda''$  couplings would cause baryon decay. The apparent HERA excess could be due to a  $\lambda'$  coupling:  $\lambda'_{ijk} L_i Q_j D_k^c \Rightarrow \lambda'_{ijk} e_R^+ d_{Rk} \tilde{u}_{Lj}$ ,  $\lambda'_{ijk} e_R^+ \tilde{u}_L \tilde{d}_{Rk}$  via the specific mechanisms  $e^+ d \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}$  with  $\lambda' \sim 0.04$ , or  $e^+ s(b) \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}$  and conceivably  $e^+ \bar{u}(\bar{c}) \rightarrow \tilde{d}, \tilde{s}, \tilde{b}$  with  $\lambda' \sim 0.3$  [23, 7, 24, 25, 26]. The absence of neutrinoless  $\beta\beta$  decay [27] imposes

$$|\lambda'_{111}| < 7 \times 10^{-3} \left( \frac{m_{\tilde{q}}}{200 \text{ GeV}} \right)^2 \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \quad (2)$$

which rules out  $e^+ d \rightarrow \tilde{u}_L$  (and  $e^+ \bar{u} \rightarrow \tilde{d}$ ), but allows  $e^+ d \rightarrow \tilde{c}_L, \tilde{t}$ . The upper limit on  $K^+ \rightarrow \pi^+ \bar{\nu} \nu$  decay [28] imposes

$$|\lambda'_{ijk}| \lesssim 0.02 \left( \frac{m_{\tilde{d}_{Rk}}}{200 \text{ GeV}} \right) \quad (3)$$

up to mixing and cancellation factors, which barely allows the  $e^+ d \rightarrow \tilde{c}_L$  mechanism. Many constraints on large  $\lambda'$  couplings, such as charged-current universality, atomic-physics parity violation and neutrino masses exclude almost all sea production mechanisms. The only mechanisms that survive this initial selection are the  $e^+ d \rightarrow \tilde{c}_L$  (down-scharm),  $e^+ d \rightarrow \tilde{t}$  (down-stop) and  $e^+ s \rightarrow \tilde{t}$  (strange-stop) interpretations [23, 7, 24, 25, 26].

The strange-stop interpretation is quite severely constrained by precision measurements at LEP1, notably the  $\rho$  parameter, which requires non-trivial  $\tilde{t}_L - \tilde{t}_R$  mixing, and limits on the violation of universality in  $Z^0 \rightarrow e^+ e^-, \mu^+ \mu^-$  decay, which impose  $|\lambda'_{13j}| \lesssim 0.6$ , so that  $B(\tilde{t} \rightarrow e^+ q)$  cannot be very small [29]. On the other hand, we recall that the FNAL upper limits on leptoquark production require  $B(e^+ q) \gtrsim 0.5$  for  $m \sim 200 \text{ GeV}$  [22].

Competitive branching ratios for the  $R$ -violating decay  $\tilde{c}_L \rightarrow e^+ d_R$  and the  $R$ -conserving decay  $\tilde{c} \rightarrow c_L \chi$  (followed by  $R$ -violating decay of the lightest neutralino  $\chi$ ) are possible in generic domains of parameter space, as a result of a cancellation in the  $R$ -conserving coupling of the lightest neutralino [7]. This is much more difficult to arrange in the down-stop interpretation, where  $\tilde{t} \rightarrow e^+ d$  either dominates (if  $m_{\tilde{t}} < m_t + m_\chi$ ) or is dominated by  $\tilde{t} \rightarrow t \chi$  (if  $m_{\tilde{t}} > m_t + m_\chi$ ). The strange-stop scenario is intermediate: after taking into account the LEP constraints, there is very little parameter space where  $B(\tilde{t} \rightarrow e^+ s) \sim B(\tilde{t} \rightarrow t \chi)$  if  $m_{\tilde{t}} = 200 \text{ GeV}$ , but considerably more if  $m_{\tilde{t}} \sim 220 \text{ GeV}$  [29].

At the moment none of the three supersymmetric interpretations is very healthy, but none can yet be ruled out.

## 8 Tests to Discriminate Between Models

More statistics should soon clarify the  $Q^2$  and  $x$  distributions, whether there is really an excess, telling us whether it is peaked in any particular mass bin, and whether there is any unusual pattern of gluon radiation.

We should also know soon whether there is really an excess of charged-current events, which would be difficult to understand in most scenarios invoking new contact interactions, leptoquarks, or even  $R$ -violating squarks (except in some interesting corners of parameter space, where cascade squark decays imitate the simple charged-current topology [21, 30]). In 1998, it is planned to run HERA in  $e^-p$  mode: most scenarios predict the absence of a signal, though one could appear in the  $e^+s \rightarrow \tilde{t}$  scenario.

Turning to other signatures, in the  $e^+d \rightarrow \tilde{c}_L$  scenario one predicts observable  $\tilde{c} \rightarrow c\chi$  decays followed by  $\chi \rightarrow \bar{q}qL, \bar{q}q\nu$ . There should be equal numbers of  $\ell^\pm + \text{jets}$  final states, and there could be  $\mu^\pm$  and/or  $\tau^\pm + \text{jets}$  as well as  $e^\pm + \text{jets}$ . These decay modes should also be observable at the FNAL Tevatron collider [7]. A first search for them has been made [18], but it does not yet have the required sensitivity.

Effects could show up in  $e^+e^- \rightarrow \bar{q}q$  at LEP2, either via contact interactions or via virtual leptoquark or squark exchange [31, 32], which might be detectable in models invoking production from the sea. Identification of the final-state quark flavours would improve the sensitivity, e.g., to  $\tilde{t}$  exchange in  $e^+e^- \rightarrow \bar{s}s$ .

One exciting possibility is the production of a direct-channel  $\tilde{\nu}$  resonance if there is a  $\lambda_{ijk}L_iL_jE_k^c$  coupling [33]. The LEP experiments have already provided some limits on  $|\lambda|$  as a function of  $m_{\tilde{\nu}}$  [34]. Unfortunately, sensitivity is rapidly lost if  $E_{cm} < m_{\tilde{\nu}}$ . It would be a shame if LEP missed out on discovering a squark or a sneutrino because it was not pushed to the maximum possible centre-of-mass energy, so let us all hope that a way can be found to operate LEP at its design energy of 200 GeV, with an integrated luminosity sufficient to exploit fully its capabilities.

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